III.

THE EARTH FROM THE GEOPHYSICAL STANDPOINT.

BY JOHN F. HAYFORD.

(*Read April 24, 1915.*)

This is a broad topic on which much intensive thinking has been done by many men. It is impossible to treat it adequately or comprehensively in the short time available.

In this address an attempt will be made to so concentrate attention on a certain few points as to tend to clarify existing ideas and to correlate them. An attempt will also be made to help in locating the lines of least resistance to future progress in the study of the earth.

The size of the earth, as well as its shape, is now known with such a high degree of accuracy that the errors are negligible in comparison with the errors in other parts of our knowledge of the earth. The probable error of the equatorial radius is less than 1/300000 part, and of the polar semi-diameter is about the same.

The three physical constants of the earth, and of its different parts, on which you are now asked to concentrate your attention are the density, the modulus of elasticity, and the strength.

It is important to know as much as possible about the density. The more one knows about the density in all parts of the earth the more surely and safely one may proceed in learning other things about the earth.

The modulus of elasticity at each point in the earth controls the behavior of the earth under relatively small applied forces.

The strength of the earth, at each point, as measured by the stress-difference at that point necessary to produce either slow continuous change of shape or rupture, decides the behavior of the earth under the greater forces applied to it.

As to density we know that the earth's surface density is about

2.7, that the density probably increases continuously with increase of depth, that the density at the center is probably about 11, that the mean density is about 5.6, and that within a film at the surface of a thickness of about one fiftieth of the radius of the earth there is isostatic compensation which is nearly complete and perfect as between areas of large extent.

The manner of distribution of the isostatic compensation with respect to depth, and the limiting depth to which it extends are but imperfectly known. Nevertheless it appears that above the depth, 122 kilometers, the compensation is nearly complete even though there may be some compensation extending beyond that depth.

Two general lines of evidence are available in determining the modulus of elasticity of the earth, that from earthquake waves, and that from earth tides.

There are many inherent and extreme difficulties in the way of securing reliable evidence as to the modulus of elasticity from earthquake waves.

To 1913 the accuracy of available observations of tides in the solid earth was insufficient to furnish a basis for reliable conclusions. Nevertheless the estimates of the modulus derived from these early observations were a fair approximation to that given by the very recent and much more accurate observations.

Dr. Michelson and those associated with him in the observation of earth tides at the Yerkes Observatory since 1913 have developed a method of observing which is of a new order of accuracy such that the minute changes of inclination at a given point due to earth tides may be determined with an error of less than one per cent.

These observations make the modulus of elasticity of the earth as a whole about like that of solid steel, namely (8.6) (10^{11} C.G.S.).

It is the modulus of elasticity of the earth as a whole which is measured in this case.

It is eminently desirable to determine if possible whether the modulus of elasticity varies with increase of depth. The Michelson apparatus possibly opens the way to such a determination. Suppose that the apparatus is used on the shore of the Bay of Fundy. Twice a day a large excess load of water is placed in the bay by the tidal oscillation and as frequently the water load is reduced below

normal. The stresses produced in the body of the earth by these changes of load applied over an area only about 30 miles wide are probably confined almost entirely to the first 100 miles of depth. The magnitude of changes of inclination produced at an observing station on the shore by the changing water load would, therefore, be dependent primarily on the modulus of elasticity of the material below and around the bay to a depth of less than 100 miles. The observations might serve, therefore, to determine a modulus of elasticity of the surface portion of the earth rather than of the whole earth.

Turn now to the third of the physical constants which it was proposed to examine, namely the strength.

Among the forces which we may consider as furnishing tests of strength are: (1) the forces involved in earthquakes, (2) the weight of continents, and (3) the weight of mountains.

The forces which produce the more intense earthquakes evidently cause stress-differences locally which are beyond the breaking strength of the material. However from earthquakes we may obtain but little information as to the strength of the earth material because the intensity of the stress-differences cannot be reliably determined. We know simply that the intensity exceeds the breaking strength of the material, at the points of rupture.

It is uncertain how great are the maximum stress-differences produced by the weight of continents. One great difficulty in computing these stress-differences arises from the fact that the isostatic compensation of continents, now known to exist, reduces the stress-differences much below what they would otherwise be. Love computed the maximum stress-differences thus reduced as .07 ton per square inch. Darwin computed the greatest stress-difference due to the weight of the continents, without isostatic compensation, as 4 tons per square inch. If each of these computations were based upon assumptions which correspond closely with the facts one should be warranted in drawing the conclusion that the maximum stress-difference caused by the actual continents supported in part by the actual isostastic compensation is between .07 and 4 tons per square inch, and that it is much nearer to the smaller than to the larger value. But a close examination of either of these computations shows that it is based

upon assumptions made to simplify and shorten the computations, which assumptions depart widely from the facts and tend strongly to make the computed stress-differences much smaller than the actual. For example, both Darwin and Love used in their computations hypothetical continents represented by regular mathematical forms in the place of the actual continents with their many irregularities. The maximum stress-difference caused by the actual continents is necessarily much greater than would be produced by the assumed smoothed out, regular, symmetrical continents.

Similarly, no adequate computations have been made to determine the maximum stress-difference due to the mountains. Darwin computed the maximum stress-difference produced by two parallel mountain ranges, of density 2.8, rising 13,000 feet above the intermediate valley bottom, to be 2.6 tons per square inch. Love, for the same mountain ranges, but with isostatic compensation taken into account, computed the maximum stress-difference to be 1.6 tons per square inch. In this case the computation indicates that the isostatic compensation reduced the maximum stress-difference to but little more than one half what it would otherwise be. Here again both the computed maximum stress-differences have been greatly reduced by substituting hypothetical smoothed-out mountains in the place of the actual irregular unsymmetrical mountains.

To the person who is trying to get a true picture of the present state of stress in the earth, two very important facts are made evident by a comparison of the Love and the Darwin computations. First, the existence of isostatic computation greatly reduces the stress-differences which would otherwise be produced by the weight of the continents and mountains. Second, the depth at which the maximum stress-difference tends to occur is evidently very much less with isostatic compensation than without it. These two conclusions, based on the differences between the two computations, are apparently reasonably safe even in spite of the same wild assumptions on which both the computations were based.

Note that even a little information as to the distribution of densities—a little information about isostatic compensation—profoundly modifies the conclusions as to the state of stress in the earth. It should, therefore, be clear why it was so emphatically stated in

an earlier part of this address that information as to the distribution of density in the earth is necessary in order to make safe progress in learning other things about the earth.

Is the earth competent to withstand without slow yielding the stress-differences due to the weight of continents and mountains, the isostatic compensations being considered? From the computations by Darwin and Love, considered in the light of the assumptions made by them to simplify the computations, I estimate that it is probable that the actual mountains and continents with all their irregularities of shape and elevation possibly produce stress-differences in some few places as great as four tons per square inch, and certainly produce stress-differences at many places as great as two tenths of a ton per square inch. The material would certainly yield slowly under such stress-differences especially when they persist continuously over long periods of time and throughout large regions. Four tons per inch is the breaking or rupture load for good granite, one of the strongest materials existing in the earth in large quantities. Two tenths of a ton per square inch is the safe working load used by engineers for good granite. There is abundant evidence from laboratory tests that the so-called yield point on which the engineer bases his estimate of safe working load for a given material is a function of the length of time the load is applied and the delicacy of the test. The longer the time of application and the more refined the test to determine the permanent yield the lower the observed yield point. In the case of the test in progress in the earth the time of application is indefinitely long and the test is extremely refined inasmuch as the minimum rate of yielding which may be detected is exceedingly small.

If an engineer wishes to know whether a bridge, or foundation, or building, or railroad rail is yielding under stress-differences which have been brought to bear upon it he looks for evidence of distress, for rivet heads popped off, scaling from the surface, settling, cracks, or even changes in microscopic structure. The geologists have made very extensive corresponding examinations of the earth. Everywhere they find evidence that the earth has yielded. On the one fourth of the earth's surface exposed to examination, the land, there is no part for which the evidence does not indicate

past uplift, or subsistence, or horizontal thrust, or cracking under tension, or cracking produced by shear, or microscopic yielding in detail such as produces schistosity for example, or some other form of past yielding to stress-differences. The physicist studying the earth must take this overwhelming mass of evidence into account and must conclude that the earth habitually yields slowly to the stress-differences brought to bear upon it. Please note that I do not assert that the stress-differences are all due to gravity.

I propose now to state what are in my opinion probably the lines of least resistance to future progress in studying the earth from the physical standpoint. I propose to outline what I believe to be the most effective methods of attack, and to indicate some of the conclusions which will probably be reached. I am led to this procedure by two considerations. First, I find it possible to state certain of my opinions as to the net outcome of past investigations most clearly in that form—and time presses. Second, I indulge the hope that such an outline which is frankly an expression of judgment based on evidence much too weak and conflicting to be proof, may possibly kindle the imagination of some man or men, and so lead to vigorous attacks upon the problem and to future progress.

In attacking the problems of the earth one should assume at the outset that the phenomena exhibited are very complicated, that they are probably due to various simultaneous actions, and that the various actions are probably closely interlocked, modifying each other, though some are probably primary in importance and others secondary. Hence the most effective method of attack is probably one which includes a general correlation of apparently widely separated ideas and facts gathered from physicists, engineers, geologists, chemists, etc., and at the same time includes intensive attacks in detail on one after the other of single features of the problems which arise and an intensive working out of the possible consequences of said features.

It should be recognized at the outset that no observed behavior of the earth clearly warrants the assumption that the material of which it is composed differs radically in any way from that accesible at the surface. It should be assumed, therefore, that throughout the earth the materials are a mixture differing from the mixture

found at the surface only as the extreme pressure and temperature conditions at great depths directly and indirectly produce differences.

It should be kept clearly in mind that the geodetic evidence from observations of the direction and intensity of gravity indicates simply the present location of attracting masses, the present distribution of density. It furnishes no direct evidence whatever as to past distributions of density, or as to changes in density now in progress. But an understanding of the present distribution of density within the earth, especially near the surface, is so necessary to a true understanding of the present state of stress and of viscous flow in the earth that an understanding of the geodetic evidence is fundamental to progress.

Computations should be made in extension of those which have been made by Darwin and Love. The new computations should, however, deal with the actual irregular continents and mountains, not with regular substitutes. The computations should also take into account the bulk modulus of the materials composing the earth, that is these materials should be assumed to be compressible. Such computations will no doubt be both difficult and long. I believe that even a moderately vigorous attack along this line will show conclusively that the earth does not behave as an elastic body under the large loads superimposed upon it by the continents and mountains. I believe that the computed stress-differences will be found to be so large that the computation will be essentially a proof of viscous yielding.

Next make the contrasting assumption that the material composing the earth is competent to withstand but little shearing stress, and that the pressure at any point is that due to gravitation acting on the mass in the column extending from the point vertically to the surface. Let it be assumed that isostatic compensation exists, is uniformly distributed with respect to depth, and is complete at depth 122 kilometers. Consider the actual topography and form a mental picture as accurately as possible of the viscous flows which would take place on the assumption that at each level the material would flow horizontally from regions of greater pressure to regions of less pressure along lines of maximum rate of change of pressure, and that the time rate of such viscous flows would tend to be pro-

portional to the space rate of change of pressure. The flows would all be found to be away from beneath high regions toward low regions, from continents toward oceans, from mountains toward valleys.

After such a picture has been clearly formed assume that the isostatic condition is disturbed by long-continued erosion and deposition producing changes in the surface elevations and surface loads. On the same assumptions as to the nature of the viscous flows as before, form a new picture of the viscous flows which would now be in progress. It will be found that under the new conditions the viscous flows near the surface would still be away from high areas and toward low areas, but in general they would be slower than before. At greater depths, however, it will be found that the viscous flows would be undertows from regions of recent deposition toward regions of recent erosion. These undertow flows would in general tend to be in the direction opposite to recent surface transportation of material. This picture would serve as a first approximation to an understanding of the mechanism of isostatic readjustment. The undertows would be found on these assumptions to extend to a considerable depth, certainly more than 122 kilometers.

Next one should picture the changes in density which would be produced by the viscous flows. The density should be pictured as decreasing in regions from which material is being carried away by the flow and increasing in regions to which the material is being carried. It will be noticed as soon as such a picture is formed that every undertow flow at any level tends to equalize pressures at lower levels. This will have a strong tendency to make the prevailing undertows occur at much higher levels than they otherwise would.

Let it be assumed that the viscous material offers some small resistance to shear and still has elastic properties to a slight degree. The condition assumed originally that the pressure at a point depends simply upon the weight of the material above that point will be disturbed thereby. Form as clear a conception as possible of these disturbances and the modifications of the flows produced by them. I believe the modifications will be found to be important, and that they will be found to be such as tend to confine the effects of surface changes of load to a depth which is a small fraction of the radius.

So much for the direct effects of gravity which it seems important to picture clearly. Next study other effects, some of which are indirectly produced by gravity.

First study the modifying effects of changes of temperature. Wherever viscous flow takes place in the quasi-solid portions of the earth there heat is necessarily developed in amount equivalent to the mechanical energy expended in overcoming the resistance to flow. This will tend to increase the volume of the material, to increase the pressure, and to raise the surface above the region of viscous flow. It is probable also that the increase of temperature will tend to weaken the material, thus emphasizing the weakening produced by the damaging mechanical effects of the flow.

This temperature effect is probably locally important.

Beneath areas of recent deposition the temperature of a given part of the buried material will slowly increase for long periods of time, on account of heat conducted up from below and prevented by the new blanket of deposited material from rising to the surface so freely as before. Conversely, beneath the areas of recent erosion the temperature of a given portion of material will decrease. The ultimate limit of change will tend to be in each case not greater than about one degree Centigrade for each thirty-two meters of depth of erosion or deposition. These temperature changes tend ultimately to lower areas of recent erosion and to raise areas of recent deposition, possibly as much as one thirtieth of the thickness of the erosion or deposition,—the temperature effect taking place much later than the erosion or deposition which initiated it.

Study next the effects which may be computed from the bulk modulus of elasticity. Beneath areas of erosion a given particle of matter tends to rise by an amount which may be computed from the bulk modulus of material, and similarly a particle tends to fall beneath an area of deposition. If the depth to which the elastic phenomena extend is as great as 122 kilometers and the bulk modulus is 500,000 kilograms per square centimeter (corresponding to granite) the rise or fall of a particle near the surface will tend to be at least 1/50th part as great as the thickness of the material eroded or deposited. This is a change so large as to have considerable effects in modifying or magnifying the actions which would

otherwise occur. Possibly this elastic change is much larger than the estimate here given. Of course if the erosion or deposition takes place in a small area only, such elastic response will be largely inhibited by surrounding material on which the load has not been directly changed. But under large areas of erosion or deposition such action must take place and extend to depths possibly as great as 122 kilometers.

Study next the modifying effects, on the phenomena already pictured, of chemical changes which are probably produced in the earth by changes of pressure. The expression "chemical changes" is here used in the broadest possible sense. A relief of pressure at any given point in the earth necessarily favors such chemical changes as are accompanied by increase in volume and reduction of density. Increase of pressure tends to have the reverse effect. Such changes tend to reinforce and extend in time the effects just referred to which may be computed from the bulk modulus of elasticity. It is important to estimate such changes as well as possible from all available evidence, such for example as that furnished by chemists, by geologists, and by such investigations of rock formation as have been conducted at the geophysical laboratory in Washington. I believe the possible effects of this kind will be found to be so large as to be of primary importance.

Evidence has accumulated during the past few years which makes it reasonably certain that with increased pressure, as at the great depths in the earth, the rigidity and the viscosity of the material also necessarily increase. This tends to cause the viscous flows to take place at higher levels than they otherwise would. This should be taken into account.

Next a reëxamination of the conceptions so far formed should be made to ascertain to what extent and how they would be modified if one started with some other reasonable assumption as to the limiting depth of present isostatic compensation or some other reasonable assumption as to the law of distribution of the compensation with regard to depth.

Next full and extensive comparisons should be made between the hypothetical phenomena on the one hand pictured as made up primarily of viscous flows, modified by some elastic effects, ini-

tiated in part by surface transfers of load, modified by changes of temperature, modified by chemical changes and in the other ways, and on the other hand the facts of the past as to the behavior of the earth recorded in the rocks and read by geologists and others. This comparison should be used to the fullest possible extent to evaluate the relative importance of the various elements in the actions.

In making this comparison of various hypothetical phenomena with the great accumulated mass of geological facts it should be recognized at once that it is false logic to reason that if a given hypothesis does not account for all the observed facts the hypothesis is necessarily erroneous. On the contrary it is true logic in dealing with such a problem as the earth seen from a physical standpoint to reason that the more facts are accounted for by a given hypothesis the more certain it is that said hypothesis is a statement of a controlling element in the complex phenomena and then to study the facts which appear neutral, or conflicting, with reference to the hypothesis, considering them as indicators of other elements of the phenomena which one should attempt to embody in other supplementary hypotheses.

I submit that in studying the earth it is a mistake to think that there is any necessary conflict between the idea that the earth behaves as an elastic body and the idea that it is yielding in a viscous manner. A body may behave in both ways at once. The earth is probably acting largely as an elastic body under small forces which change rapidly and at the same time is yielding in a viscous manner to forces of larger intensity which are applied in one sense continuously for long periods.

The object of this address will have been accomplished if it serves in time to arouse the imagination and interest of some one and to guide him to greater effectiveness in attacking the problems presented by the earth as seen from the geophysical standpoint.

College of Engineering, Northwestern University.
Evanston, Ill.